

CHAPTER A-2 GEOLOGIC INFORMATION REQUIRED FOR DAM AND LEVEE RISK ASSESSMENT

A-2.1 Introduction

A-2.1.1 Statement of Problem

Dam and levee risk assessments require site-specific knowledge on foundation materials and active geologic processes that could affect them. Geologic conditions may constitute a flaw in a dam or levee component that could lead to a potential failure mode, and active geologic processes may cause changes in conditions that lead to component flaws and potential failure modes. Geologic materials form the foundations for almost all dam and levee systems because, ultimately, every dam or levee system rests upon earth materials that have been formed through geologic processes. As a result, a reasonable level of knowledge of geologic conditions at a dam site or under a levee system is needed for understanding site-specific hazards, and the potential failure modes that arise from these hazards. Comprehension of geologic processes that have led to, or could change, site conditions is also needed in order to identify and characterize potential failure modes. Thus, understanding geologic site conditions and processes is essential for dam and levee risk assessments.

Geologic processes are complex and variable through time and across a range of spatial scales. Because geologic process can be highly variable, geologic deposition and erosion are, in turn, highly variable. In addition to the inherent variability of geologic processes and resulting deposits and landforms, our ability to characterize the deposits is often constrained by investigative techniques, limited time, inadequate funding, and other logistical constraints (i.e., site accessibility for gaining more knowledge or capturing natural variability). The characteristics and distribution of geologic materials can be estimated with a moderate amount of confidence where geologic processes of deposition and erosion are well understood, because known physical laws control these processes and can be applied to site-specific conditions. In other words, using knowledge of general geologic processes to identify likely site conditions is often necessary where knowledge of specific geologic conditions is difficult or impossible to obtain. The three-dimensional characteristics of geologic materials at a specific site only rarely



are evaluated with complete confidence, and uncertainty in deposit variability can be substantial if geologic processes are not well understood. As a result, dam and levee safety risk assessments are well served to incorporate knowledge of geologic processes that have, or could, act at any particular dam site or levee system.

A-2.1.2 Significance of Problem

Because of inherent geologic variability and the limited knowledge of geologic processes and deposits at a given site, the ability to build well-constrained subsurface stratigraphic models almost always results in some degree of uncertainty in geologic-related failure modes. In order to develop reasonable and defensible models of foundation materials for risk assessments of dams and levee systems, the geologic depositional framework must be understood and the uncertainties in that framework must be acknowledged. Without an understanding of geologic processes and deposits, subsurface models may not adequately represent site conditions, probable failure modes may be either over-emphasized or under-appreciated, and hazard assessments may not be defensible. In these cases, risk assessments may or may not adequately identify key risk-driving failure modes, nor properly capture their likelihoods.

An adequate understanding of dam or levee foundation conditions is critical for evaluating structure performance and estimating the likelihood of various event nodes. Summarizing site-specific geologic information on detailed plan, profile, and cross-section drawings is essential for developing an adequate understanding of the site conditions and their uncertainties. This is essential for any risk analysis, and for communicating interpretations of foundation conditions to technical reviewers and decision makers. The importance of this communication is reflected by the many dam and levee failures and incidents attributed to poor site foundation conditions and/or interactions at the foundation interface. Many failures have occurred because of incompatibilities between the foundation and dam or levee materials placed upon it, which often results from inadequate understanding of geologic foundation conditions. In some cases, foundation materials are unable to withstand the demands imposed by the structure and increased hydrologic loads that come with dams (i.e., higher, longer duration reservoir pools) and levees (i.e., higher, more persistent river stages). In other cases, failures have occurred because of

geologic conditions (sometimes in combination with seepage and/or loading from the reservoir) that were not adequately anticipated or addressed during design or construction.

In short, geologic site conditions often strongly affect dam and levee design, construction methods, foundation treatment, and post-construction foundation and structure performance. As a result, understanding site-specific geologic and geotechnical characteristics is critical for identifying credible potential failure modes, estimating foundation performance during static conditions or hydrologic/seismic loading, and capturing the range of uncertainty in foundation performance. The task of evaluating, summarizing, and portraying geologic and geotechnical information is important for dam and levee safety assessments. Importantly, effective communication of this information is essential for estimating the level of risk, as well as the degree of uncertainty in the risk estimates.

A-2.1.3 Purpose and Objective

The objectives of this chapter are to (1) provide information for practitioners to understand common geologic processes, and their associated deposits and landforms, that are likely to be significant for identifying and assessing potential failure modes at a given dam site or levee system, and (2) highlight effective means of communicating geologic knowledge to risk assessment teams. The focus of this chapter is on geologic processes, deposits, and landforms that are most commonly characterized in risk assessments for dams and levees. This chapter also provides guidance for portraying site-specific geologic conditions for dam and levee safety risk assessments, and is supplemented by example drawings (*Geologic Example Drawings.pptx*).

A-2.2 Evaluating and Summarizing Geologic Data for Dam and Levee Risk Assessments

A-2.2.1 Approach

For many dam and levee projects, the volume of available geologic and geotechnical data can range from sparse to overwhelming. For sites containing abundant data, the process of sorting through available information, identifying applicable and relevant drawings, photographs, and other datasets, and assimilating the data into a useful and concise format is extremely important for understanding foundation characteristics and potential failure modes. For other projects, the amount of available data may be extremely limited. In these cases, it is even more important to

employ all available data for making reasonable interpretations of site geologic conditions. This may involve interpreting the limited existing information in the context of geologic processes that may have acted at the site and controlled or influenced existing conditions, and placing the available knowledge within the context of reasonably common geologic processes governed by basic physical laws. A primary role of an experienced engineering geologist on dam and levee risk assessment teams includes providing a scientific basis for interpreting likely site conditions given limited information. It is also important for the geologist to provide reasonable ranges for foundation properties given available data and, importantly, communicating the range in geologic conditions to risk assessment team members.

The effort spent reviewing, evaluating, understanding and portraying subsurface information is highly variable and often determined by the scope and/or stage in the safety evaluation process. The level of detail may vary according to project scope, budget, or schedule, and the need for a balance between these competing constraints should be acknowledged. The dam safety process ranges from initial screening level efforts, to Potential Failure Mode Analysis (PFMA), and to detailed risk analysis studies that are part of an Issue Evaluation Study (IES) or Dam Safety Modification Study (DSMS). The levee safety process include use of the Levee Screening Tool (LST), or more detailed work as part of a Higher-level Risk Assessment (HLRA) for a specific levee system. Engineering geologic input is needed in all of these analyses, but at different levels of detail according to scope, budget, and schedule. An iterative approach to the foundation evaluations and analyses is often required as the details of the dam/levee are added and evaluated, as more information develops during the risk assessment regarding geologic and geotechnical conditions, structure performance, and consequences. An initial geologic understanding of site conditions should always be developed in the earliest phases of the risk assessment, because subsequent phases of work use the geologic information as basic site constraints; therefore, it is critical that the geologic data, interpretations, and ranges of uncertainty are all communicated to the risk assessment team.

Comprehensive geologic analyses for large or complex projects may require many months of teamwork. The need for a detailed level of effort must be justified and weighed with many considerations, including resource requirements on other projects that may be a higher priority.

Additionally, some initial evaluations may not have identified key failure modes, and review and search for additional information may be needed as the team becomes more focused on specific risk-driving failure modes. The appropriate level of effort for the development of subsurface data must be determined by the team responsible for using the information (and an experienced advisors, as needed) based on the amount of information, details of primary failure modes, and evaluation scope. Some data may be developed in later phases after the team captures the level of uncertainty associated with primary risk drivers.

A collaboration between the engineering geologist and geotechnical engineer is essential for developing interpretations based on the understanding of geologic conditions, particularly when data are sparse and limited. This is an opportunity for the geologist to improve knowledge about material properties, depositional environments of alluvial units, bedrock structural conditions, and other considerations that influence the performance of a dam, a levee, or their foundation materials. This collaborative process can significantly influence risk estimates, and should be conducted by individuals specifically involved in the risk assessment to maintain consistency in the team's knowledge and expertise.

A specific list of the primary questions or most important parameters is a useful method to guide data collection, evaluation and reporting. Prior to sorting through available information and identifying essential data, it is important to formulate key questions associated with credible potential failure modes that will be evaluated. This list should be produced and prioritized in the context of evaluating dam or levee and foundation performance. An event tree is an excellent guide for determining what data are most important. Sorting through the available information to determine its relative importance to dam or levee safety requires significant experience and should be assigned accordingly. Care should be taken to reference the source documents for all essential extracted information to assist in building the dam or levee safety case and assuring interpretations and conclusions have clear links to supporting data.

Plan maps, cross sections, profiles, tables, graphs and photos are the most useful products for helping summarize a large amount of foundation data. In some cases, much of the required subsurface information may already exist on plan and profile drawings and photographs which are adequate for the early meetings in the assessment process. Usually there is initial work

required months in advance to organize the data for ready access to conduct the risk analysis and discuss potential failure modes. The engineering geologist and geotechnical engineer should be prepared to present information to the risk assessment team that explains key embankment and foundation conditions that strongly influence potential failure modes.

The process of identifying, evaluating, understanding, portraying and communicating the most important foundation information is critical for improving the project team's knowledge, reducing uncertainty in risk estimates, and enabling better communications with a broader audience (including reviewers and decision-makers). Dam and levee foundation information should be portrayed with the dam/levee information to develop an understanding of potential interactions. The geologic/engineering drawings developed during this process are important products for understanding and communicating foundation conditions. Sometimes these drawings are hand-drawn or observations made on as-built drawings. Data availability is more important than final drafted CADD drawings, especially during the initial analysis. The primary goal of the data evaluation and summary process is to maximize the understanding of the parameters most important for evaluating potential failure modes and estimating future performance. The process is also essential to help identify key data gaps. The ability to capture this information succinctly in a set of foundation drawings can save many hours during the risk analysis by eliminating the need to continually search through multiple reports, borehole logs, and unorganized data and documents.

It is not practical to develop a list of foundation and embankment data requirements that is applicable to all dams and levees, or all potential failure modes. Every dam or levee and foundation has unique characteristics. Therefore, the most effective way to communicate foundation data must be customized for each project, and must be related directly to failure modes of concern. Examples of various types of foundation drawings are included in the PowerPoint file "Geologic Drawing Examples.pptx intended to be used along with this chapter.

A-2.2.2 Primary Data Requirements

Most foundation deficiencies, such as seepage leading to internal erosion and bearing capacity, will be at least initially considered on nearly every embankment dam or levee. Failure modes

may be sequentially related such as excessive foundation settlement leading to overtopping or cracking followed by seepage failure. Other failure modes can be attributed to less common, but specific soil or rock conditions that may be ruled out if absent. The following general list of potential seepage-related failure modes helps illustrate the process of data collection, evaluation and communication. A similar list could be developed for other non-seepage related failure modes (e.g., slope stability).

Examples of Potential Seepage-Related Failure Modes:

- Erosion of the sandy or silty foundation soils exiting downstream or possibly exiting into coarse natural deposits or coarse fill material such as berms, or into open discontinuities within bedrock, etc. Piping progresses from downstream to upstream.
- Erosion of embankment material into coarser gravelly foundation deposits or into open discontinuities in a bedrock foundation. Piping progresses upstream or may slope upwards.
- Scour of embankment material at the foundation contact due to seepage occurring in coarse gravel deposits or within open discontinuities in a bedrock foundation. Erosion may progress along a continuous feature, or slope upwards. Seasonal reservoir loading fluctuations may influence progression.
- Scour of finer natural silt and fine sand materials in the foundation that are adjacent to highly permeable gravel materials capable of higher velocity flow.
- Scour, erosion, or stoping within the embankment and/or surficial deposits associated with concentrated foundation seepage in karst foundations or highly permeable gravel layers or channels.
- Seepage and erosion beneath structures (e.g., outlet works, spillway walls) exiting downstream into a broken drain, the ground surface, or into coarser materials or open discontinuities in bedrock.
- Excessive differential foundation settlement leading to embankment cracking and piping.

The investigation and assessment of these (and many other) potential seepage-related failure modes leads to the development of important questions that will help guide the collection,

evaluation and presentation of subsurface data. Much of this information can and should be portrayed on a set of drawings with associated figures, plots and photographs. Some of the important data associated with these potential seepage and piping failure modes include:

- Geologic descriptions of foundation soil properties and geomorphology
 - Geologic descriptions of foundation materials from borehole or test pit logs
 - Location of all exploratory holes shown on plan map and sections
 - Geologic descriptions of materials exposed on the surface nearby
 - Driller's notes related to material properties or behavior and conditions that effected the character of drilling (heaving sands, fluid losses, etc.)
 - Interpretation of range of expected material properties based on understanding of depositional environment and local geomorphology (particularly highly permeable or highly erosive material, geometry, and internal variability)
 - Interpretation of range of expected continuity of various materials based on depositional history and available data (including erosive materials, roof-forming cohesive materials, highly permeable coarser gravel beds)
- Descriptions and properties of bedrock associated with seepage and piping
 - Orientation of discontinuities (joints, shears, bedding, faults)
 - Width of discontinuities (openness)
 - Spacing of discontinuities
 - Infilling characteristics of discontinuities (extent, physical properties)
 - Continuity of open joints, shears, bedding, faults, and other structural features
 - Photographs of rock exposures, including construction records, cutoff trench, representative exposures in the area
 - Geologic descriptions of rock units, material types
- Material properties and descriptions of the embankment and/or foundation soils, including:
 - Gradations (graphs of all available lab results in dam and foundation)

- USCS classifications with plus 3-inch fraction included
- Atterberg limits (plasticity, liquid limit)
- Consolidation/swell pressure data
- Shear strength
- Adverse chemical properties
- Density (in place density of foundation soils before construction, in place density of foundation after construction, construction control data including percent compaction, moisture content, etc.)
- Permeability and water loss zones from borehole drilling records
- Artesian pressures and confining layers
- Testing memorandums and reports
- Penetration data (SPT, CPT, Vane Shear, Becker Penetration Tests – drilling methods can influence results significantly)
- Cementation
- Dispersion potential
- Descriptions, sketches and photos of in-situ soil materials to help understand issues such as:
 - point to point contact of gravel (e.g., matrix vs. clast support, likelihood of open-framework gravels)
 - gravel floating in a sand matrix
 - thin layering of different materials that may have been averaged by sampling
 - influence of gravel on SPT or other penetration testing
 - depositional environment providing clues to estimate continuity
- Geologic records from surrounding area providing insight into possible conditions in dam foundation (quarries, borrow excavations, road cuts, water well logs, regional mapping, foundation investigations for other structures, etc).
- Available published soils maps and reports from USGS and NRCS
- Surface and borehole geophysical logging, when applicable

- Design and Construction Records related to seepage interception and control (original construction and subsequent modifications)
 - Design Memorandums (written descriptions of original design considerations and intent, etc.) especially those related to seepage analysis, filter design, stability analyses, etc.)
 - As-built drawings showing location of all seepage control features (original and all subsequent additions or changes). This includes:
 - Toe drains
 - Downstream seepage control berms and/or filters
 - Embankment filters and drains
 - Upstream seepage control blankets
 - Cutoff trench dimensions, location and conditions
 - Outlet works and spillway
 - Material descriptions, foundation maps and records from construction and foundation reports
 - Photographs of embankment material placement or borrow areas
 - Photographs of foundation soils or bedrock exposed during construction records, including overhangs and steep bedrock exposures
 - Photographs of foundation treatment (or lack of), especially the treatment of open discontinuities in bedrock
 - Chronologic summary of seepage evaluation and modifications made throughout history of project
 - Location of all known seepage areas or springs pre-dating construction
 - Written descriptions of subsequent design considerations and changes/improvements performed to mitigate seepage concerns
 - Grouting records showing location of all grout holes, water tests, grout takes, grout mix, pressures, grout hole communication, refusal criteria and observations of grout travel and break-outs
- Instrumentation data needed for risk analysis

- Location of all embedded instruments shown on geologic sections
- Time series plots of piezometer response to reservoir fluctuations for the complete project history
- Correlation plots of pool elevation versus piezometric response
- Projections of piezometer responses to reservoir/pool levels above historic maximum
- Written evaluation of piezometer data as related to dam or levee performance history and changes over the life of the instruments
- Maximum piezometer readings plotted on geologic sections
- Measured and predicted (where appropriate) piezometric pressure gradients along potential seepage paths (depicted on geologic sections)
- Surface and internal deformation data that could be related to stability concerns, or seepage and erosion problems
- Location of all known surfacing seepage locations downstream
- Sand boil and other sediment accumulation locations
- Hydrographs of all measured seepage and leakage flow data
- Correlation plots of pool elevation versus seepage and leakage response
- Weir flow data tied to reservoir levels
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- Consultant observations made throughout the history of the project
 - Note any recommendations for remedial actions
 - Document actions taken as a result of consultant review
 - Document dam or levee performance following implementation of remedial actions

A-2.3 Portraying Geologic Site Data and Characteristics

A-2.3.1 Drawings Necessary to Summarize and Communicate Foundation and Embankment Material Properties and Behavior

The partial list of useful data provided above serves as a starting point for evaluating potential failure modes or risk estimates. With either sparse or abundant site geologic data, it is necessary to assimilate and summarize the most important information for communication with the risk assessment team. A set of non-exaggerated (i.e., true scale such that vertical and horizontal scales are the same), detailed, full sized drawings combining geological, geotechnical, and instrumentation data is essential. In most cases it is possible to incorporate nearly all significant information onto geologic cross sections, which then serve as a means for evaluating potential failure modes.

A-2.3.2 Developing Detailed Cross Sections to Depict Geology, Material Properties and Instrumentation Response

There is no single “correct” way to develop geologic cross sections (or profiles) and display data. Such guidance would stifle the imagination of those responsible who should be continually striving to improve the management and communication of this information and make it site-specific. Sometimes it makes most sense to draft these sections using CADD software. Sometimes hand-drawn cross sections are the quickest and most effective, or annotations made on existing sections. Automated input of borehole data onto geologic sections may save time initially in some CADD systems, though these computer-generated cross sections always require additional thought, interpretation, geologic evaluation, and work to assure the appropriate meaningful data are displayed legibly.

Cross sections and sometimes profiles are important to develop at the location of potential foundation problems and where piezometer and observation well data may provide a better interpretation of seepage conditions. The team should discuss the location and data requirements of cross sections or profiles most important to pending discussions. The three-dimensionality of the geology/structure geometry cannot always be adequately communicated with one cross section. Often several sections, along with a detailed plan map, may be required. A cross section along the outlet works is generally needed, particularly for conduits through the

embankments where seepage erosion will be evaluated. At a minimum, a typical section is required that shows the foundation interpretation, along with embankment zoning and design features.

Regardless of the method or approach used in developing cross sections, some guiding principles and basic data requirements include:

- Non-exaggerated scales (this is necessary to see true thicknesses, slopes, and gradients)
- Full sized drawings NOT drafted to use half size, in order to plot very detailed information on the vertical scale (e.g., gradations, soil classification, uniformity coefficients)
- Scales generally between 1' = 20' and 1" = 40' to fit borehole information
- Location of the top and bottom of piezometer influence zones and all other significant instrumentation
- Piezometer readings tied to specific reservoir elevations (maximum historic for example)
- Phreatic surface from available piezometers and predicted phreatic surface for higher reservoir levels up to the top of dam
- Separation of actual data from interpretations (use solid, dashed, and dotted lines along with question marks to help portray relative uncertainty and include notes).
- Interpretations of vertical and horizontal continuity of important foundation layers, lenses or units (carefully show what is known and unknown). Where interpretations are made, include reasoning and logic as notes on the section so confidence and uncertainty can be communicated. In sedimentary rock, a straight line interpretation of the top of bedrock often misses a common occurrence of cliffs and benches.
- Unified Soil Classification System symbols for all borehole sampling, including plus 3 inch material by volume (sorting out differences between field and lab classifications)
- Percent fines, sand and gravel when evaluating potential seepage and piping flow paths and susceptibility to erosion in granular materials

- Avoid the use of computer generated symbols that force continual reference to a legend to understand (rely more on USCS classifications and gradations)
- Assure all computer-generated soils data are legible (this requires manual drafting in most cases)
- Distances and directions of drill holes when projected onto cross sections
- Labels for the location of every other intersecting cross section. (This is generally shown as a short vertical line near the top of the drawing).
- Dam stationing for all profiles near centerline
- Embankment zone design features (cutoffs, grout curtain, found. treatment) and appurtenant structures (outlet works, spillway, etc.)
- All seepage control features and associated “plumbing” (toe drains, berms, upstream blankets, cutoff trench, drainage blankets, rock drains, relief wells, etc)
- Continuity of foundation soil units of concern
- Continuity of rock lithology or discontinuity features important to foundation performance

A-2.3.3 Developing Detailed Plan Maps

In order to adequately evaluate dam performance and estimate risks associated with various potential failure modes, it is essential to clearly understand the location of all design and construction elements and everything associated with monitoring the structure, particularly the geotechnical exploration and instrumentation. The plan map serves this purpose and as the key drawing to show the locations of all cross sections. This requires a plan map drawn at a scale sufficient to portray the necessary details of all important information.

The level of detail required and the amount of significant information varies between dam projects and is generally influenced by the number of explorations, the amount of construction related features (e.g., grout curtains, key walls, special treatment zones, dental concreted and slush grouted bedrock contacts, fillet walls), and the complexity of the seepage control features (e.g., drains, berms, blankets, filters and associated “plumbing”). Dams with a large amount of data may require a layering approach when developing the plan map in order to toggle on and off

various data sets, depending on the specific needs of the analysis. Various CADD systems have been used to successfully develop these types of plan maps which can be saved as working PDF documents for easy distribution and use. Sometimes more than one plan map is required, for example when a top of rock contour map is used to portray rock properties and discontinuity information, or when ground water contours are needed in combination with piezometers, observation wells, relief wells and other data useful for evaluating seepage.

For initial failure mode evaluations existing plan maps may be adequate. However, it is often necessary to update maps by adding recent explorations, instrumentation, and noted design changes or additions. The need to improve and update the plan map should be assessed several months prior to the risk assessment meeting, along with updating the as-built sections and profiles with relevant new information. These maps should be updated as part of any dam safety program, independent of risk analysis.

Basic information displayed on the plan map often includes the following:

- Topography of the dam and surrounding area (updated as needed to represent current conditions)
- Inspection trenches, cutoff trenches, grout lines, concrete bulkheads, concrete fillets, special treatment zones. (Note: these features are typically shown as dashed/hidden lines on the plan view showing the dam.)
- Outline of the dam with dam stationing
- Location of all cross sections and profiles being used with the current plan map
- Location of the outlet works, spillway and stilling basin
- All seepage control features including drains, drainage blankets, stability berms, relief wells, water conveyance pipes, limits of filters, etc. All exploration holes drilled at the site, including post-construction drilling, test pits, trenches
- Location of all instruments, including active (and abandoned) piezometers, weirs, inclinometers, surface deformation points, crack monitoring gages, (identify active piezometers)
- Geologic contacts, especially the limits of materials influencing potential failure modes

- Faults and shear zones as mapped in the foundation or nearby
- Pre-existing springs noted prior to dam/reservoir construction/impoundment and current springs differentiated
- Abandoned gas/oil/water wells, farm ponds (springs), sinkholes, caves, etc.
- Outline of original river channel prior to diversion or construction and during construction if within the embankment or structure footprint.
- Location of other pertinent features (e.g., gravel pits, borrow pits and other excavations, utilities, etc)
- Location of important photographs
- Location and types of distress features
- Any deviations from original design due to difficulties encountered during construction.
- Haul road locations (which may be indicative of over-consolidation of embankment soils) or potential for impacts on chimney filters from vehicular traffic, resulting dramatic changes in soil properties adjacent to the haul road)

Possible sources of geologic mapping, soils information, and imagery to supplement project records during the initial data collection phase (see resource list at end of this chapter) include:

- USGS geologic maps and EROS Data Center for imagery
- BLM maps and aerial photographs
- Natural Resources Conservation Service (NRCS) soils mapping
- State Geological Surveys (often linked to aerial photographs and local and regional soil and rock mapping)
- Terraserver
- Google Earth
- Google Maps LiDAR (using Terrain Layer Feature)
- Local academic researchers
- Libraries with historic aerial photography and remote-sensing data.

A-2.4 Common Analytical Methods

A-2.4.1 Analysis and Use of Photogrammetric Methods for Geologic Characterization

With the advent of rapidly improving digital photography technology and photogrammetric processing software, photogrammetry methods have become an important tool at the disposal of engineering geologists for use in characterizing geologic features.

Terrestrial photogrammetry methods can be used in conjunction with traditional Brunton compass surveys to map geologic foundation conditions for existing or planned spillways, abutments, embankments or other engineered structures. This mapping should be completed so that the geology is well understood, the results are permanently and quickly documented, and any design assumptions can be verified readily. This technology enhances the level of geologic mapping for foundation acceptance and provides concise archival documentation. Figure 1 is an example of a photogrammetric model used to evaluate the orientation of discontinuities in an arch dam abutment.

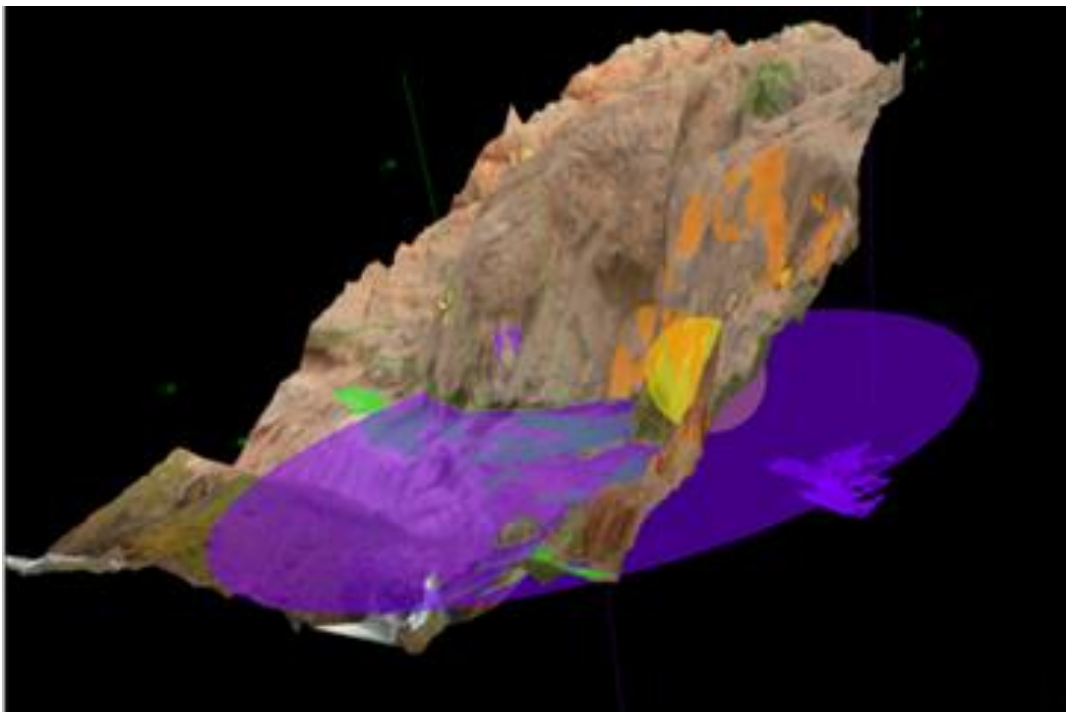


Figure A-2-1 Arch dam abutment photogrammetry 3D model used to measure orientation of major joints and shears

Digital photographs, from a commercial off-the-shelf camera, are taken of the geology exposed within the structure foundation areas. A variety of methods can be used to take the digital photographs, including hand held, tripod, survey rod, balloons, and most recently, Unmanned Aerial Systems (UAS, commonly called “drones”). Obtaining data via UAS is being more prevalent with advancing airframe technology.

Oriented stereo images consisting of digital terrain models can be produced that allow the user to evaluate geologic discontinuities in the model. Accurate digital elevation models and orthophotographs can be created from these photos (Figures A-2-2 and A-2-3). These data tools are useful for a variety of project types including:

- Geologic mapping for design and acceptance of foundations/rock slopes/tunnels.
- Geologic mapping of geomorphology trenches (i.e., fault mapping and paleo-flood hydrology mapping, etc.)
- Borrow Quantities
- Concrete Deterioration Quantification
- Concrete Dam deformation
- Embankment Dam deformation
- Plant and Structural Measurements
- Difference modeling for rock scour, rock stability and sedimentation analysis.
- Generation of topographic maps.

Photogrammetric mapping is applicable to existing dams, as well as to new construction to ensure the details of the geology, concrete structures and embankments are quickly and accurately documented for current and future use. Photogrammetric models can be practical ways to obtain remarkably accurate data; these methods have many advantages over traditional mapping and surveys. The software available to construct three-dimensional models using digital imagery has reached the point of acceptable accuracy and ease to make the use of 3D geologic reconstructions commonplace in high-end site characterization and design projects.

Advantages for using digital photogrammetry include:

- Field work is less time consuming and more accurate.
- Hundreds of discontinuities can be measured instead of just a few
- Ability to quickly produce stereonet for discontinuity analysis
- Statistical confidence is greatly improved
- Rope access can be minimized, greatly decreasing worker safety concerns
- Topography can be developed at the same time
- Surfaces can be added to the model to see where they intersect
- Accurately measure any object in the model
- Provide concise archival documentation
- Geologists can quickly evaluate multiple projections and three-dimensional models for verifying outcrop data

Figure A-2-2 Example of photogrammetric model of a new spillway foundation illustrating ortho-rectified site plan (details in Figure A-2-3.)

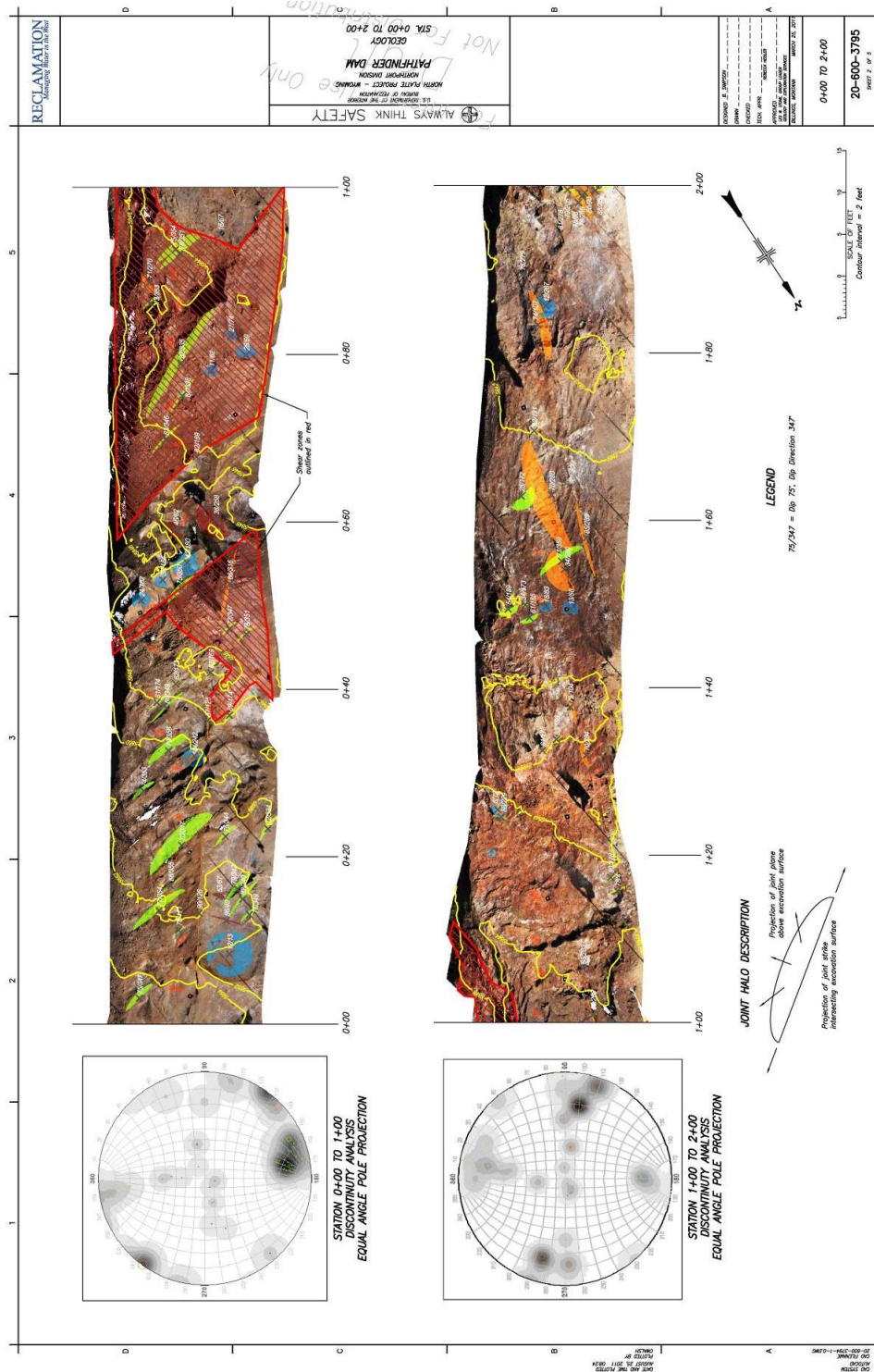


Figure A-2-3 Details of geologic maps and stereonet of the spillway foundation using processed photogrammetric models

A-2.4.2 Analysis and Use of Construction Photographs and Field Records

Construction photographs have proven to be important records for documenting and understanding embankment placement and foundation conditions. All photographs, including historic aerial photographs should be considered extremely valuable, and every effort should be made to locate, review, sort and annotate existing photos from all available records.

Contemporaneous photos from construction documents are particularly valuable, and all photographs from pre-construction and construction files should be reviewed and incorporated into the geologic site model. Existing photographic prints should be carefully scanned at high resolution, and digital and original files should be preserved. It is effective to “re-publish” important photographs within current documents to help support the dam or levee assessment and efficiently communicate site foundation conditions. In addition, field records from construction (e.g., inspector's notebooks, Project Engineer's log book, construction payment modifications) can be extremely valuable and should be provided whenever available.

Sometimes it is possible to contact individuals present during construction, and conduct an interview to obtain preciously undocumented site information or construction sequencing that may be valuable for the risk assessment.

Examples of some types of information obtained from evaluation of photographs:

- The type, degree and quality of foundation treatment
 - Slush grouting
 - Dental grouting
 - Clean up details, equipment, technique, areas cleaned
 - Treatment (or lack, thereof) of faulted, sheared and fractured rock
- The shape and configuration of bedrock or soil surfaces
 - Overhangs in bedrock
 - Steep bedrock areas left in place
 - Cutoff trench shape, extent, steepness, conditions, etc
 - Location of construction roads that may influence embankment performance
(such as cracking at steep road cuts remaining in foundation)
- The details of rock discontinuities

- Orientation
- Aperture of open joints and bedding planes, etc.
- Material properties of infilling material
- Details of backslope of cutoff trench
- Embankment placement details
 - Thickness of lifts
 - Compaction effort and type of equipment
 - Compaction problems adjacent to outlet works and other structures
 - Filters and drain locations, properties and placement
 - Temporal discontinuities during placement and treatment of surface when construction is re-initiated.
- Seepage areas downstream
 - Location and extent of seepage problem areas
 - Seepage changes over time
 - Flood fighting efforts; sand bags, dikes, berms, filters, etc.
 - Relief well flow
 - Sediment transport into downstream seepage areas
- Conditions of materials sampled during explorations
 - Undisturbed soil or rock samples in sampling barrels
 - Soil or rock samples in core boxes
 - Test pit and trench wall exposures showing materials and depositional environment, stratigraphy, continuity, range of variation, etc.
 - Spoil piles from excavations depicting material types, oversize, etc
 - Amount of oversize (plus 3 inch) material that may not be represented by laboratory testing
 - Cementation or apparent cohesion in exposed soil slopes
- Locations of older stream channels and soil deposits of interest
 - Aerial photographs taken early in the project showing old stream channels that may influence foundation seepage
 - Old channels that may have been backfilled during construction

- Extent and size of boulder, cobble and gravel materials exposed during construction
- Evidence that foundation soils contain lenses that are too coarse to be sampled accurately in drill hole information; especially the evaluation of gradation data.
- Historic channels and their migration over time
- Photographs of test pit walls can reveal more than a gradation analysis of samples.
- Details of Construction
 - Sequencing of fill placement and diversion if applicable
 - Methods, equipment, and techniques used
 - Locations of temporary construction features such as haul roads, borrow pit types and locations (include final depth, areal extent, and any restoration that may have been performed)
 - Record of flood damage
 - Erosion features that formed on temporary foundation and embankment slopes
 - Point of completion at which a work suspension occurred
 - Construction or design details that may not be adequately documented

A-2.4.3 Analysis and Use of Geomorphic Data for Dam and Levee Foundation Evaluation

Geomorphology is the scientific study of the formation, alteration, and configuration of landforms, including the depositional and erosional processes active during their formation. Through these studies, geologists are able to understand more about the physical environment during deposition and subsequent modifications that may have occurred through erosion or other processes. For most embankment dams and levees founded on soil, a detailed understanding of the geologic depositional environment is essential to augment exploration and performance data and help interpret material property variations and continuity. In most cases, geotechnical borehole data can be supplemented and developed into a coherent site geologic model by using geomorphic data on alluvial deposition and soil-development data.

An experienced geomorphologist provides knowledge and understanding of depositional and erosional processes that inform risk assessment teams about the continuity and characteristics of alluvial, colluvial, and landslide deposits in the site area. These provide constraints on the extent

and permeability of alluvial deposits that may control seepage (for example, beneath levees) or concentrated leak erosion (e.g., beneath dam embankments). This is particularly critical in areas underlain by alluvial foundations (especially glacial outwash) where subsurface data are limited or inadequate, but the continuity of potentially erosive or permeable materials needs to be estimated for the risk analysis. Geomorphologic information also provides guidance about the history of riverine erosion and lateral migration, which can help assess likelihoods of erosional potential failure modes along levee systems. Geomorphic expertise applied to analysis of aerial photography is also essential for identifying landslides near dam sites and in reservoir basins to address slide-related overtopping and other failure modes. For most levee investigations, geomorphic mapping of the exposed soils (especially channel fill deposits) is essential for guiding detailed site characterization activities such as geophysical or geotechnical exploration. Site geologic maps that include delineation of surficial deposits, as identified by geomorphic analysis, provide value to risk assessments when combined with quantitative performance data on, for example, previous seepage or levee slope instability locations. The scope of surficial geologic mapping can vary widely and can be customized to address overall site hazards or target site characteristics related to specific failure modes.

Geomorphic analysis often utilizes several data sets, as determined by specific project needs or potential failure modes. For understanding the history of riverine migration or locations of alluvial erosion near levees, analyses may include review of a time series of vertical aerial photography, including vintage images that allow delineation of episodes of ground disturbance that pre-date existing land uses. Coupled with high-resolution topographic data from Light Detection and Ranging (LiDAR) surveys, time-series provide data to identify landforms related to potential failure modes by digitally removing vegetation and developing “bare-earth” topographic data.

Geomorphic mapping of surficial features are often interpreted in conjunction with standard surface and subsurface data to develop a consistent site geologic model. Other data sets can be obtained from geological publications, bulletins, reports and boring data from a variety of Federal and State agencies, including Departments of Transportation, the State Geological Surveys, USGS, and private engineering firms. More detailed subsurface information, generally

the logs of specific borings drilled on or near the structure, can be used to develop cross sections and to further refine the surface interpretations.

Subsurface sampling of alluvial deposits is inherently limited, even assuming that individual boreholes are representative of alluvial deposits. Delineating geomorphic landforms and surficial deposits at a dam site or along a levee system provides a means to understand the geologic context of individual boreholes, and helps define the continuity and extent of permeable or impermeable strata that may control or influence seepage, piping, or other failure modes. Evaluating and understanding near-surface stratigraphy and continuity in complex alluvial deposits is often best accomplished through geomorphic analysis of aerial photography, historical vintage topography, and subsurface information. Depositional units in these environments are often characterized by very rapid and complex changes over short distances, both vertical and lateral. The combination of a wide spacing between drill holes, very small sample size (diameter of borehole over space between borings), sample disturbance, mixing, poor recovery of gravel and larger sizes, and difficulty in viewing sedimentary structures in recovered samples often results in overly simplified and incomplete geologic models that do not reflect natural variability. Techniques more useful for understanding continuity and developing a subsurface model include:

- Test pits
- Trenches
- Examination of nearby exposures including road cuts, quarries, borrow pits, exposed foundations
- Aerial photographs (from the earliest available to the most recent in 5-10 year increments if available)
- Topographic Maps (7-1/2 USGS topographic quadrangles)
- Regional maps of surficial geology or soil (USGS, NRCS)
- Academic reports, theses and guidebooks from conference field trips
- Photographs and maps of original foundation excavations (cutoff trench, outlet works, and other structure foundation exposures)

- LiDAR imagery that allows the geologist to “remove” vegetation and better evaluate surface morphology and infer geologic conditions
- Examination of old aerial photos to determine potential impact associated with recent land use such as sand and gravel pits, mining, and dump sites.

The purpose of these geomorphic investigations is generally to (a) determine the areal distribution and physical characteristics of the various surficial deposits, (b) reconstruct the general geologic history of the area, (c) conduct subsurface stratigraphic correlation of various geologic environments of deposition as an aid in determining foundation and underseepage conditions, (d) provide a technical basis for supporting estimates of material properties and continuity for a risk assessment, and (e) help in the identification of other landforms important to site hazards, such as landslides.

Even with limited exposures and sparse sampling it is often necessary to make “reasonable” best estimates of material properties and continuity based on knowledge of local geomorphology. A qualified geologist (experienced and trained in soils analysis) can assess the surface morphology and evaluate the environment(s) responsible in the development of surface features. Then, using principals of sedimentology and stratigraphy, a geomorphologist can link processes from modern analogs and infer the nature of the deposits in the subsurface. Naturally, the degree of uncertainty in these estimates is important to consider, discuss and document.

The following list is provides examples of geologic environments (depositional models) that might be considered when developing interpretations of subsurface soil conditions. Because the geologic processes of erosion and deposition may differ substantially among various geologic environments, knowledge of geologic environments can provide guidance for interpreting foundation conditions. At sites where subsurface data are limited or insufficient for defining foundation conditions (e.g., the extent or permeability of paleochannel sands beneath a levee embankment), knowledge of geologic processes and depositional environments can provide analogous information to estimate the likelihood of potential foundation flaws. Knowledge of site geologic environments can help identify, or perhaps rule out, various geologic conditions beneath a levee or dam (e.g., landslide material in a dam abutment, or continuous permeable

sand strata beneath a levee). For example, at sites where fine sand or silt is known to exist in some samples, the continuity of this stratum can be estimated based typical conditions observed at other sites or based on known geologic processes. Limited subsurface data can be coupled with known characteristics of similar depositional environments to develop an internally consistent geologic model that helps assess the range in possible site conditions.

Materials sampled in the foundation may be representative of:

- Limited, isolated lenses perhaps as small local streams or older meander belts
- channel fill sediments left by point bars in slowly moving streams on inside bends and thus with limited continuity
- Overbank deposits draped on the floodplain during floods, possibly continuous
- Continuous but sometimes narrow stream channel fill that could extend upstream to downstream possibly in sinuous form
- Continuous, laterally extensive layers of sandy material from a lacustrine environment (beach or deltaic deposits) or a broad outwash plane downstream of a retreating glacier or distal deposits within an alluvial fan
- Abandoned channels and swales partially or completely backfilled that can act to focus seepage (channel-fill deposits)
- Abandoned terrace deposits along the active channel or valley
- Windblown silt deposits expected to form continuous layers
- Natural levees or low ridges that flank river channels and influence subsequent deposition during flooding (crevasse splay deposits, etc.)
- Backswamp deposits of fine-grained sediments deposited in broad shallow basins during river flood stages
- Dune or beach sand deposits in an aggrading delta environment
- Fault zones with abrupt changes in material juxtapositions at depth
- Various combinations of several deposition environments that need to be considered as a system, with possible material continuity/connections independent of depositional or geologic continuity

- Rapidly changing depositional settings where fine sands can be overlain by silty or clayey deposits capable of forming a roof
- Erratic ice or water-laid deposits containing layers or lenses of very fine sands or rock flour in direct contact with coarse grained and very pervious deposits.
- Drowned valley deposits.

The character and evolution of floodplain deposits can provide essential clues useful for interpreting material properties and continuity. This is especially true for foundations where sampling is limited. Floodplains are formed by a complex interaction of processes governed by stream power and the character of the sediment, as well as natural dams formed by ice or landslides and more recent man-made dams. The deposition can range from coarse-grained high energy confined environments to unconfined fine-grained low energy environments, each with unique geomorphological features. Understanding and defining the range of expected environments for a particular site helps form the basis of important interpretations and judgment that are not possible using the physical sample data alone.

For dams, the upstream to downstream continuity of deposits is the primary concern. For example: what is the likelihood that a sandy or gravelly channel deposit exists in the foundation and extends from upstream to downstream, or that a series of interconnected similar deposits exist? How does particle size change along this pathway and is the pathway straight or sinuous? For levees, the lateral continuity of deposits extending from the waterside to the landside of the levee is the primary concern. For example, does an old meander channel extend below the levee from the riverside to the landside of the embankment? Are there pinch-outs in the old buried channels where porewater pressure could be elevated? Where are the surficial low permeability deposits thin? A geologic model is required to understand the existing conditions and subsequently estimate these probabilities.

In many geologic environments the likelihood of any particular material being laterally continuous is dependent on many variables (e.g., distance from primary sediment source(s), nature of sediment available for transport, depositional setting in the channel, etc.). For this reason, large dams with large footprints often have lower probabilities of material continuity than small dams. Conversely, the foundation of small dikes and levees in the same geologic setting

are often more likely to have lateral continuity; and spatially small features have a higher likelihood of being able to cross the entire feature and create a vulnerability that could lead to failure.

In some areas, geomorphic techniques are useful for evaluating whether seismic or hydrologic hazards. Paleoseismic investigations include trenching (and logging), surface mapping, and landform evaluations (from aerial photographs, topographic maps and LiDAR imagery) to map surface features suggestive of active or inactive faulting. Geomorphic surface mapping may be required to establish relative or absolute age estimates for displaced or undisplaced features, and assess the timing and magnitude of past large earthquakes.

Geomorphic analytical techniques have proven to be an important method for understanding the occurrence or non-occurrence of past or ancient flood events (paleo-floods) throughout the United States and the world. Historic and systematic (gaged) streamflow data sets typically used in hydrologic models for dam and levee risk assessments are often less than about 100 years long. Through geomorphic techniques, paleoflood analyses can yield information for extending the hydrologic record with greater confidence to rare or extreme annual exceedance probabilities. Radiocarbon dating of organic matter (small particles of charcoal, seeds and other organics) or other numerical and relative dating techniques provide estimates of flood frequency extending over thousands of years. These data can be very important for informing the estimates of flood recurrence probabilities by including rare or extreme flood magnitudes that occurred hundreds to thousands of years ago. The application of geomorphology techniques to ancient flood deposits can provide a record of extreme reservoir inflows or riverine stages, enabling a better understanding of the timing and magnitude of extreme floods. These techniques can improve hydrologic models used to estimate recurrence relationships of large floods, essential for dam and levee safety studies. Paleoflood analyses have been shown to improve confidence in hydrologic loading, including flow-frequency relationships (i.e., river stage-frequency for levee systems, and reservoir pool-frequency for dams).

A-2.5 Example Geologic Analysis for Risk Assessment

A-2.5.1 Potential Failure Mode: Seepage and Piping in Karst Terrain

Embankment dams constructed on untreated karst foundations have significant and unique hazards that can lead to potential failure modes related to seepage and piping beneath dams or levees. The potential for karst or karst-like features in an area should be recognized by a risk assessment team and considered as a potential failure mode. The effects of karst dissolution in the subsurface beneath a dam or levee may result in catastrophic, uncontrolled crest lowering, or in excessive seepage or piping that could result in removal of dam or levee embankment material and thus crest lowering. This section presents key characteristics of karst terrain and its formative geologic processes, provides a few examples of karst features encountered at dam construction sites in the United States, and summarizes site investigations that can be used for characterizing karst features and karst-related potential failure modes.

Karst terrain is a geologic term applied to areas that are strongly affected by near-surface dissolution of carbonate rocks (primarily limestones and dolomites) and evaporite rocks (primarily gypsum and salt). Karst terrain commonly contains features related to subsurface dissolution, including sinkholes, breccias (broken rock deposits), ground subsidence, dry valleys, sinking streams, caves, springs and rock pavements. Karst develops through chemical dissolution and physical erosion of soluble rock strata by the action of near-surface (vadose zone) water and deeper (phreatic) groundwater. The acidity of groundwater often controls the location and rates of dissolution, with mildly acidic groundwater that fluctuates elevation through time causing the highest rates and amounts of dissolution. Karst features commonly develop along cracks, crevices, joints and bedding planes in soluble rock strata, and is often controlled structurally by joint sets, fractures, or faults. As a result, structural patterns in the soluble rock mass often control the pattern and extent of karst development of an area. Over geologic time, karst terrain forms an interconnected network of solution features; where extensive dissolution occurs in the shallow subsurface, sinkholes form by collapse of underground voids, and may be filled partially or wholly with locally derived “collapse breccia” (Figure A-2-4). In some cases where dissolution of rock produces voids in bedrock as well as overlying unconsolidated material, sinkholes can develop catastrophically (Figure A-2-5).

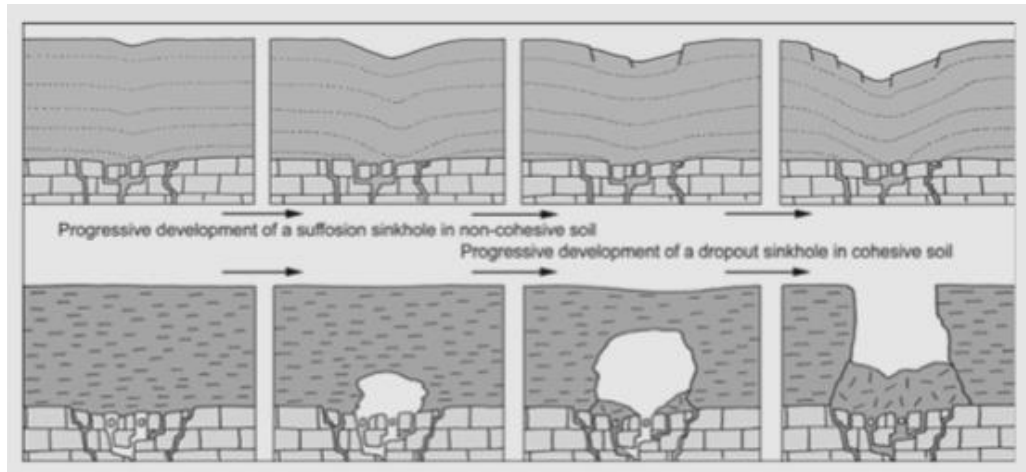


Figure A-2-4 Development of typical sinkholes in non-cohesive soils and cohesive soils

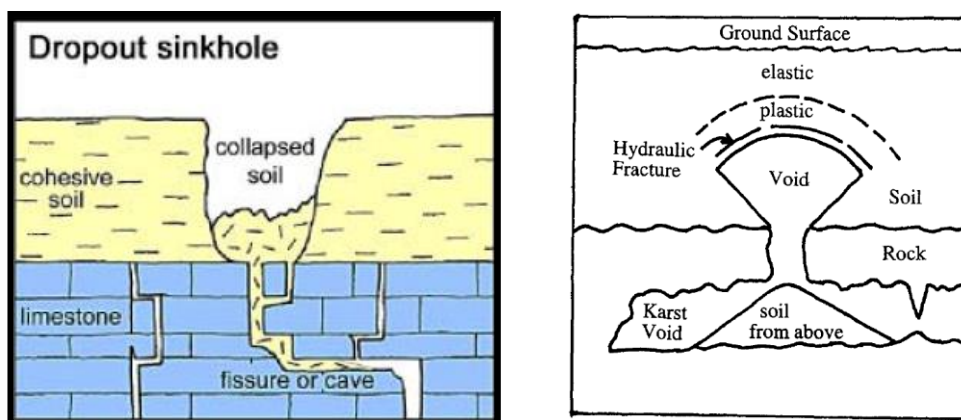


Figure A-2-5 Diagrams of sinkhole development in soil.

A-2.5.2 Examples of Karst Features at Selected Dam Sites in the United States

Karst features have been encountered during and after construction activities at several dam sites in the United States, and are probably also locally present under some levee systems. For dams, because karst-related dissolution occurs along continuous and interconnected fractures and joints, the likelihood of an upstream to downstream seepage path can be high. Wolf Creek Dam (southern Kentucky), which is located in a region of extensive caves as a result of geologic conditions favorable for karst development, is known to overlie large karst-related dissolution

caves. Center Hill Dam (central Tennessee), which is located in a similar geologic region, overlies rock strata that contain karst dissolution along near-vertical joints sets. The size and continuity of karst-related groundwater pathways and openings may differ significantly depending upon local and regional geologic and groundwater conditions. Knowledge of site-specific geologic conditions in areas of potential karst dissolution is often necessary for adequately identifying and characterizing potential karst-related failure modes. Other examples of karst-related issues encountered in dam foundations are given in Figure A-2-6.



Figure A-2-6 Photos of karst areas exposed by construction projects, clockwise from upper left): a) Karst in the Tennessee River at the new Chickamauga Lock, Chattanooga Tennessee; b) Rock foundation exposed underneath J. Percy Priest Dam, Tennessee; c) Beech Creek Limestone pavement below Patoka Lake Dam, Indiana; d) Solution widened joint exposed in the cutoff trench during construction of Clearwater Dam, Missouri

For levees, dissolution along fractures or other structural discontinuities may provide a near-surface pathway for seepage and piping from riverside to landside areas. The possibility of surface collapse “sinkholes” related to near-surface dissolution pose a potential failure mode that may or may not be easily perceived in advance. Again, knowledge of site-specific geologic processes is critical for identifying and characterizing potential karst-related failure modes.

Extreme karst terrain can occur in evaporite strata (i.e., gypsum, salt), usually in arid regions or where easily erodible evaporites are buried and protected from rainfall. Existing solution channels in gypsum can enlarge quickly if groundwater flow paths or rates change, such as when a reservoir begins impounding streamflow. For example, the proposed Upper Mangum Dam in Oklahoma was abandoned before construction because of gypsum deposits. In 1989, catastrophic failure of Quail Creek Dike (near St. George, Utah) was related, in part, to dissolution of gypsum strata beneath the embankment.

Dam and levee foundations with highly permeable, open or partially open solution networks capable of transporting high volumes of soil can progress more rapidly to failure. Substantial erosion of joint fill material can progress with no visible signs of distress, reducing the opportunity for detection and intervention. The surface area of the void feature that is in direct contact with the embankment can have a direct influence on erosion rates and the probability that erosion leads to failure. Features that are continuous at the foundation contact are more critical than smaller voids, which isolate leakage within bedrock strata. Even after extensive site investigations, it may be very difficult to quantify the extent of dissolution and the quantity of potential seepage. Joint patterns may indicate likely seepage directions, but accurately locating all potential karst openings may be difficult.

Through time, dissolution cavities may be filled in by either collapse (forming breccias) or slower accumulation (forming colluvial infill deposits). The amount and character of the infill material may influence groundwater pathways and thus can affect the likelihood of seepage or piping development. However, the amounts and erodibilities of infill material within dissolution cavities are often highly variable, and the level of uncertainty in these parameters should be estimated in the analysis of karst-related potential failure modes. In addition, grouting operations and construction activities may have partially filled dissolution cavities and improved erodibility of the infill material, but all possible seepage pathways may not be eliminated. As a result, the degree of interconnectedness of seepage pathways should be captured during site characterization phases of the risk assessment.

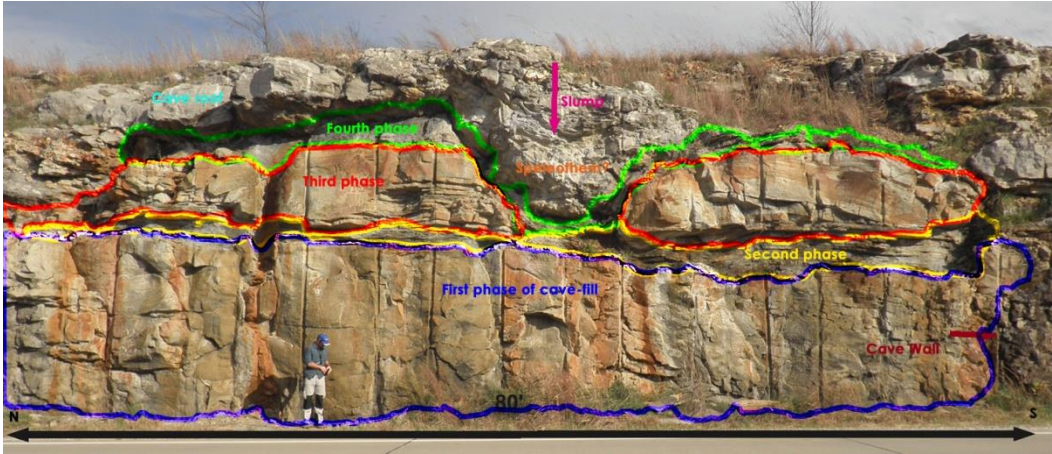


Figure A-2-7 Karst features exposed on Highway 39, Dade County, Missouri
[\(http://mississippian-cave-fill.blogspot.com/\)](http://mississippian-cave-fill.blogspot.com/)

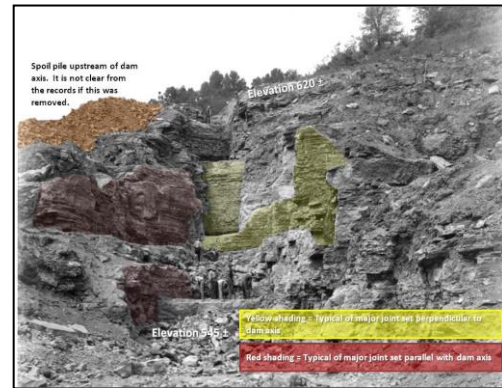


Figure A-2-8 Examples of karst features at Center Hill Dam, Tennessee, (left) Migration of soil into a karst feature near the left rim; (right) Joint faces exposed in core trench during construction

A-2.5.3 Key Types of Information for Characterizing Karst-related Failure Modes

In addition to subsurface borehole data and permeability testing, the type of information that has proven useful for evaluating karst foundations includes:

- Detailed photographs of exposed bedrock in the foundation during construction:
 - Location and size of open or solutioned joints and cavities that are exposed to the overlying foundation and/or embankment structure

- Details of infilling material – nature, type, classification and how open the features are where infilling is exposed. Does the infilling appear to be weathered in-place residual material or is it transported material?
- Higher velocity flows are much more likely where gravel deposits are found instead of clay infilling.
- Continuity of solution features – how likely are these features to provide an upstream/downstream connection?
- Orientation and character of controlling geologic structure including joint faces which may be visible during construction (How are the features open to the overlying soils? Are they open "windows" with particular apertures or are they "slot like" with pinnacles and vertical fissures?)
- Amount of weathering on exposed solution features in the rock. Are the walls smooth which may indicate higher velocity water flow? Are the walls fluted which indicate smaller scale turbulent water flow which may be a little more restricted? Are there cave deposits such as flowstone visible?
- Construction foundation reports and design data:
 - Descriptions of foundation treatment – was the entire foundation cleaned? Was the rock foundation treated or did the designers depend on a small core trench leaving most of the foundation untreated resulting in high gradients into open unfiltered features?
 - Grouting quantities, large takes, interconnections – Was there a particular pattern to the interconnections noted during grouting programs? Are there areas with very high takes only under gravity grouting such as large takes for casing grout?
 - Slush grouting or dental concrete location and extent – were all exposed features cleaned and treated with dental concrete or did construction only clean out and fill certain features? Were features cleaned across the entire foundation?
 - Bulkheads at large openings – were caves exposed in the foundation or in the core trench?

- Records of exploration borehole fluid losses, voids, etc. – for certain types of drilling, the only record of karst features exposed in the subsurface may be tool drops and fluid losses.
- Drawings, sketches or sections showing solution features
- Piezometer Data: Careful, detailed evaluation of piezometer response data can be particularly difficult in karst terrain. Piezometers will respond differently depending upon whether they are located in the dam embankment; in a completely open karst drainage path; in a partially blocked drainage path; or in a completely blocked karst opening. If the context of the instrument is not known, then its behavior is difficult to understand. Essential points for evaluating instrumentation include:
 - Evaluation of headwater and tailwater influence on piezometers indicating permeable connectivity. The head difference and reaction time is important to understand.
 - Sudden increases or decreases in water levels indicating shifting drainage and flow conditions. These can sometimes be correlated with high headwater events or construction-induced changes.
 - Long term changes in the instrument response, or tighter correlation with headwater and/or tailwater over time. Subtle decrease in water levels may indicate that flow paths are opening and providing more drainage.
 - Increasing gradients are more important to look for than simply changes in water levels
 - Determination of whether gradients are into or out of the bedrock and if gradients fluctuate seasonally between these conditions.
 - An appreciation for the sampling interval of the instrument. Piezometers only read monthly often provide very little useful data in karst. In special cases such as nearby construction, daily readings are more helpful. Karst foundations are often very reactive to drilling, water pressure testing or grouting and can react instantaneously to such operations. Automated piezometers recording at 15 minute intervals are far more useful in these situations.

- Review of published information on regional karst development and review of exposed rock in the vicinity of the project.
- Review of existing geophysical investigations
 - DC resistivity methods have been useful in defining contrasts between limestone and water or air filled voids. Resistivity can be analyzed in 2D, but the 3D tomographic methods may also be of use in locating potential voids. These investigations are most effective when combined with targeted drilling or where previous boreholes help inform the geological model.
 - Ground penetrating radar is effective where the overlying soils are not clay
 - Self potential difference models have been useful to show seepage paths, especially in combination with resistivity or with ground penetrating radar.
 - Downhole geophysics, testing and photography can also add to the understanding of the rock underneath the dam:
 - Gamma-gamma methods can identify clay layers
 - Cross-hole P and S wave velocity measurements can be used where tightly spaced boreholes are available.
 - Borehole image logs: the Optical and Acoustical Televiewer (OTV/ATV) provides static pictures of the borehole circumference with depth.
 - CCTV cameras can be used to explore large openings or assess flow rates where water is filling a hole. They can be useful in large openings, particularly if a light source can be introduced in a separate drill hole
 - Microgravity surveys can also provide data because the negative anomalies produced by this method represent “missing mass: which can be interpreted as either an air filled, or water filled void.
 - Permanently installed electrical resistivity grids for real time monitoring to assess changes with time (DC resistivity and self-potential)
- Review of existing borehole data
- In foundations affected by dissolution, interpretation of conditions between boreholes is extremely challenging (Figures A-2-9 and A-2-10). Even in relatively simple cases, vertical

boreholes are commonly insufficient to describe existing conditions, and inclined boreholes are preferred. Projections made between drill holes require an appreciation of the uncertainties and an understanding of the geometry of the karst system. Interpretation should be carefully informed by:

- Anticipated depth to rock.
- Extent of the karst development in the area – can large openings be expected or is the karst development small and perhaps primarily along bedding? Is there significant vertical karst development? Are there numerous mapped sinkholes in the area? Are there numerous springs in the area?
- Structural controls presented by area jointing, faulting and bedding patterns.
Intersections of joints or fractures in the rock are likely to be more eroded and widened by previous dissolution.

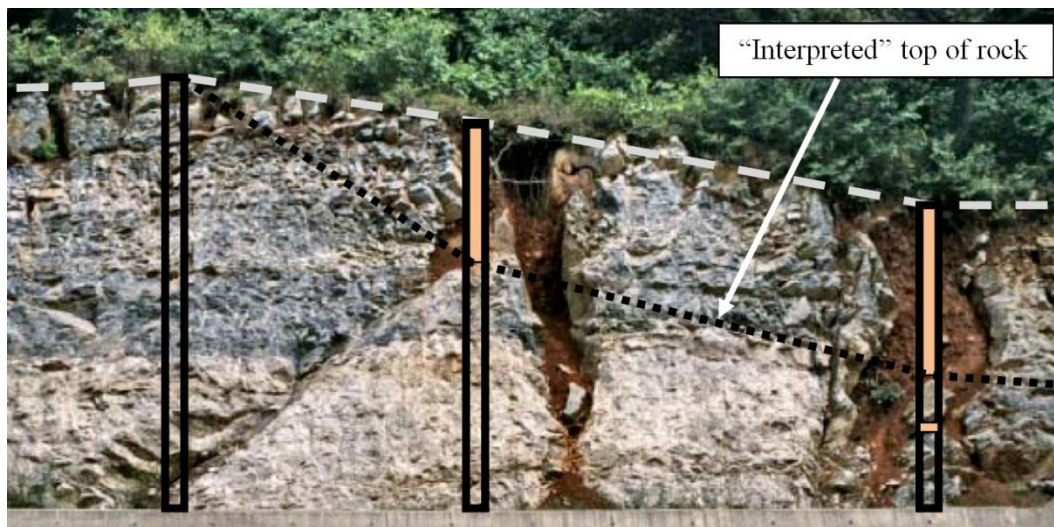


Figure A-2-9 The perils of “connecting the dots” between drill holes in karst terrain. This photograph, taken from Waltham and Fooks, has regularly spaced boreholes. The vertical development of karst shown in this rock cut means that drawing a line between adjacent boreholes can yield an incorrect interpretation

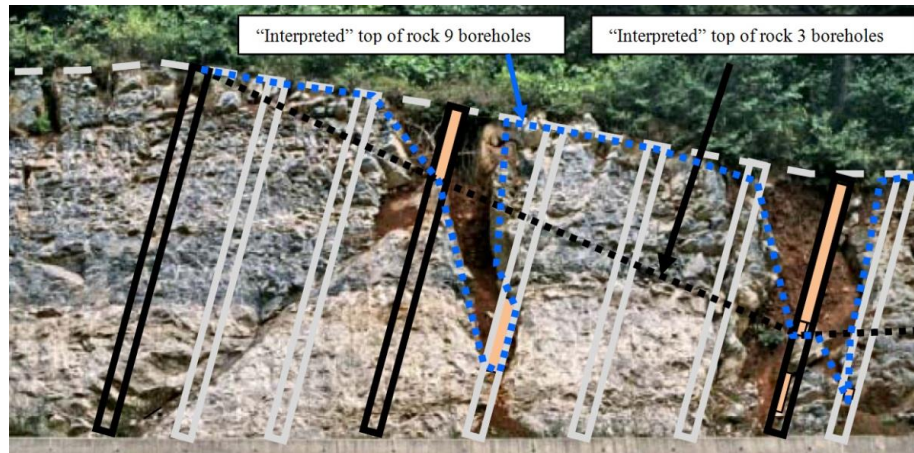


Figure A-2-10 Drilling “interpretation” based on inclined boreholes for the same number of boreholes and interpretation based on additional inclined boreholes. Using several inclined boreholes improves interpretation and confidence in geologic model.

- Anticipated depth of the epi-karst zone – this can vary both regionally and locally depending upon the topography, water’s access and changes in lithology.
- Changes in rock lithology which can change the pattern of the karst development. When less soluble rock is encountered, karst development tends to continue and enlarge along the bedding contact, even if overlying development is more vertical.

Supplementing a drilling investigation with geophysics, areal geological mapping and a firm grasp of the geological context of the site will improve the geological interpretation and produce a more reliable understanding of potential failure modes essential for estimating dam safety risks. Computer modeling can be instrumental for sorting and displaying large amounts of data in three dimensions. This is especially true for projects with previous remedial work, including grouting or cutoff wall construction, since the volume of available information can be overwhelming to sort, plot and understand. The advancement of GIS capabilities, CADD modeling and relational databases to store large volumes of data give the modern geologist or engineer more ready access to enormous amounts of information. Evaluating large projects requires integrating all of this data into a usable and understandable form.

Individual risk estimates associated with karst dissolution can be highly variable, especially when data are poorly organized and the foundation is not understood

Risk assessments can benefit greatly from the input of geologists with experience in karst evaluations working to develop a geologic model that represents the best estimate of subsurface conditions based on available supporting data. It is only after such a complete and detailed evaluation is finalized that the need for (and type of) additional investigations and studies can be properly assessed.

A-2.6 Important Reading for Engineering Geologists

Terzaghi, K. V., “Engineering Geology on the Job and in the Classroom”, Harvard Soil Mechanics Series No. 62, Vol 48, April 1961, p. 97-139

Terzaghi, K. V., “Past and Future of Applied Soil Mechanics”, Harvard Soil Mechanics Series No. 62, Vol 48, April 1961, p. 97-139

Terzaghi, K. V., Effects of Minor Details on the Safety of Dams, Am. Inst. of Min. and Metal. Engrs., Technical Publication No. 215, Feb. 1929

Deere, Don U., “Engineering Geologist’s Responsibilities in Dam Safety Studies”, ASCE publication Foundation for Dams, Asilomar Conference Grounds, Pacific Grove California, March 17-21, 1974.

Burwell, Edward B., Roberts, George D., The Geologist in the Engineering Organization”, Application of Geology to Engineering Practice, the Berkeley Volume, Geological Society of America, 1950.

A-2.6.1 Geologic Resources for Dam and Levee Geology Drawings

Woerner, E.G., Dunbar, J.B., Villanueva, E., and Smith, M. (2003), “Geologic Investigation of the Middle Mississippi River”, (ERDC/GSL TR-03-7); United States Army Corps of Engineers, Engineering Research and Development Center, Geotechnical and Structures Laboratory

Glynn, M.E and Kuszmaul, J. (2004). “Prediction of Piping Erosion Along Middle Mississippi River Levees—An Empirical Model” (ERDC/GSL TR-04-12) *Technologies and Operational Innovations for Urban Watershed Networks Research Program*, United States Army Corps of Engineers, Engineering Research and Development Center, Geotechnical and Structures Laboratory <http://www.dtic.mil/cgi-bin/GetTRDoc?AD=ADA428221>

Kolb, C. R. (1975). “Geologic control of sand boils along Mississippi River levees,”

Technical Report S-75-22, United States Army Corps of Engineers,

Waterways Experiment Station, Vicksburg, MS.

<http://www.dtic.mil/cgi-bin/GetTRDoc?AD=ADA014274>

Shaffner, P.T., “Geologic Data and Risk Assessment; Improving Geologic Thinking and Products” United States Society on Dams, 21st Century Dam Design – Advances and Adaptations, 31st Annual USSD Conference, San Diego, CA, April 2011
<http://ussdams.com/proceedings/2011Proc/545-570.pdf>

A-2.6.2 National Geology and Mapping Resources

<http://nationalmap.gov> - USGS National Map Viewer and Download Platform

<http://ngmdb.usgs.gov/> - USGS National Geologic Map Database

<http://websoilsurvey.nrcs.usda.gov/app/HomePage.htm> - Soil Surveys

<http://earthquake.usgs.gov/> - USGS Earthquake resources

<http://lmvmapping.erd.usace.army.mil/> - ERDC Geology maps of Mississippi

<https://corpsmap.usace.army.mil/> - Corps maps program

<http://www.cflhd.gov/resources/agm/> - Geophysics resource, Federal Highway Administration

<http://msrmaps.com/> - USGS air photos and maps – free

<http://www.esri.com/data/free-data> - ESRI links to free GIS web based data

<http://www.stategeologists.org/> - Association of American State Geologists – links to all state geological surveys web pages

<http://www.techtransfer.osmre.gov/NTTMainSite/Initiatives/NMMR/nmmr.shtm> - National Mine Map repository includes abandoned and active mines

<http://www.usbr.gov/library/> - USBR Library page has many useful links inside and outside of USBR

A-2.6.3 USACE Geologic Data Collection

Subsurface Drawing and Data Requirements for PFMA, Risk Analysis, Modification Reports, Issue Evaluations, etc; Geology, Geotechnical Engineering and Instrumentation. USACE LINK (Technical Excellence Network) for Geology:

[https://ten.usace.army.mil/Files/4/5/5/9/Drawing%20and%20Data%20Requirments%20for%20PFMA%20and%20Risk%20Analysis%20\(5\)%20\(8\).pdf](https://ten.usace.army.mil/Files/4/5/5/9/Drawing%20and%20Data%20Requirments%20for%20PFMA%20and%20Risk%20Analysis%20(5)%20(8).pdf) -

Additional references and information provided for USACE employees under “General Information” USACE Link: <https://ten.usace.army.mil/TechExNet.aspx?p=s&a=CoPs;104> -

Technical Excellence Network site for Geotechnical Engineering, USACE link:

<https://ten.usace.army.mil/TechExNet.aspx?p=s&a=COPS;8> -

A-2.6.4 Levee Tools and Data

lmvmapping.erd.c.usace.army.mil - Geomorphic Maps: Lower and Middle Mississippi Valley Engineering Geology Mapping Program, Technical Reports, US Army Corps of Engineers, Engineering Research and Development Center,

<http://nld.usace.army.mil/egis/f?p=471:1:3936126924813426> – National Levee Database

<http://maps.crrel.usace.army.mil:7778/lstp/f?p=480:1> – Levee Screening Tool

<http://maps.crrel.usace.army.mil:7778/apex/cm2.cm2.map?map=UOC> – CorpsMap

http://www.fema.gov/plan/prevent/fhm/lv_lamp.shtm - FEM

A-2.6.5 Bureau of Reclamation Publications

Engineering Geology Field Manual (pdf) vol 1 and 2:

<http://www.usbr.gov/pmts/geology/geoman.html>

Earth Manual part 1 (*Earth Manual* comprehensively covers the engineering of earthen structures. Extensive bibliographies supplement each chapter. An exhaustive index references and cross-references hundreds of terms):

http://www.usbr.gov/pmts/materials_lab/pubs/earth.pdf